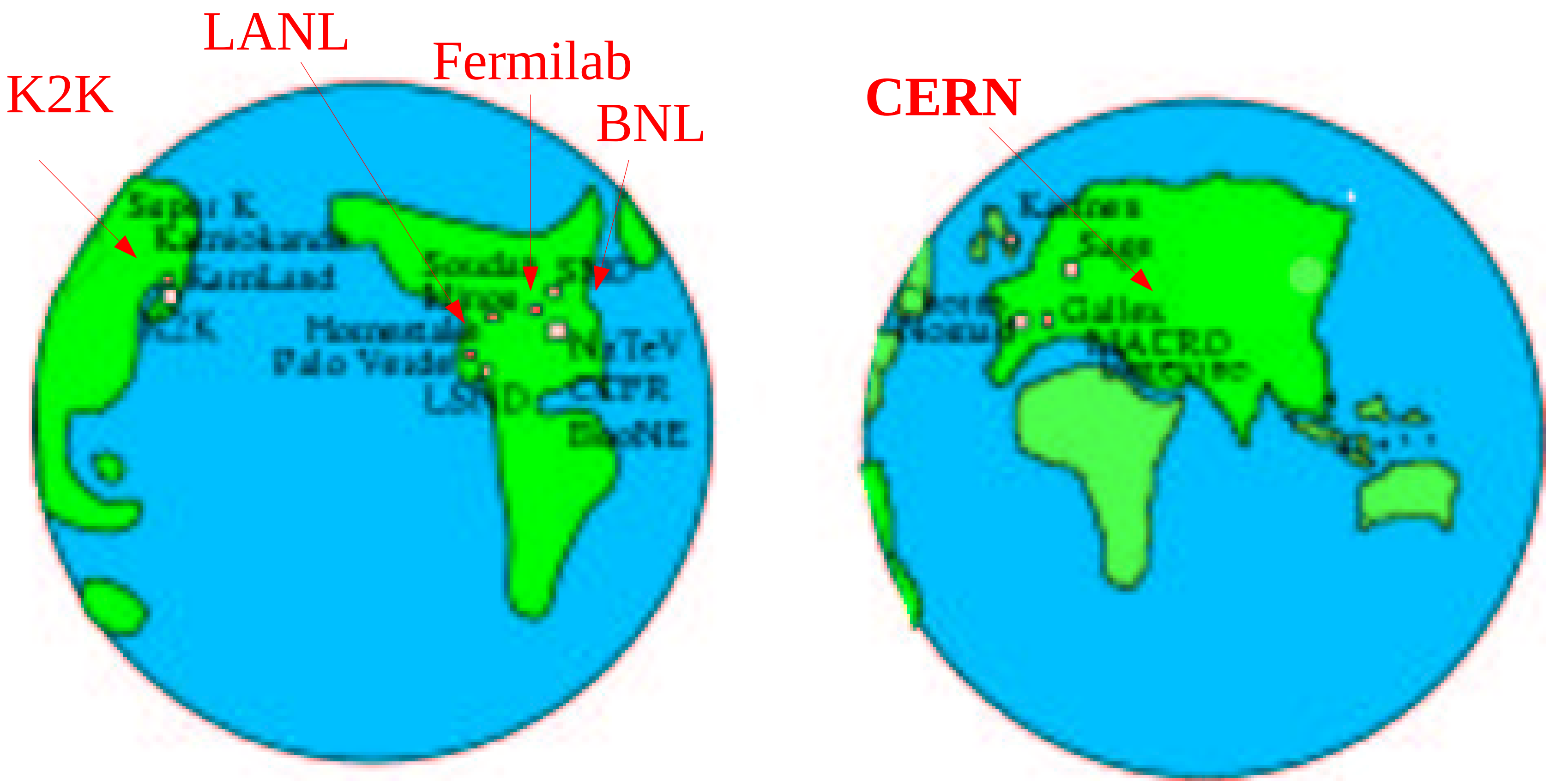
Oscillation Physics at Accelerators

A Whole ν World



Pushing the boundaries: the atmospheric result

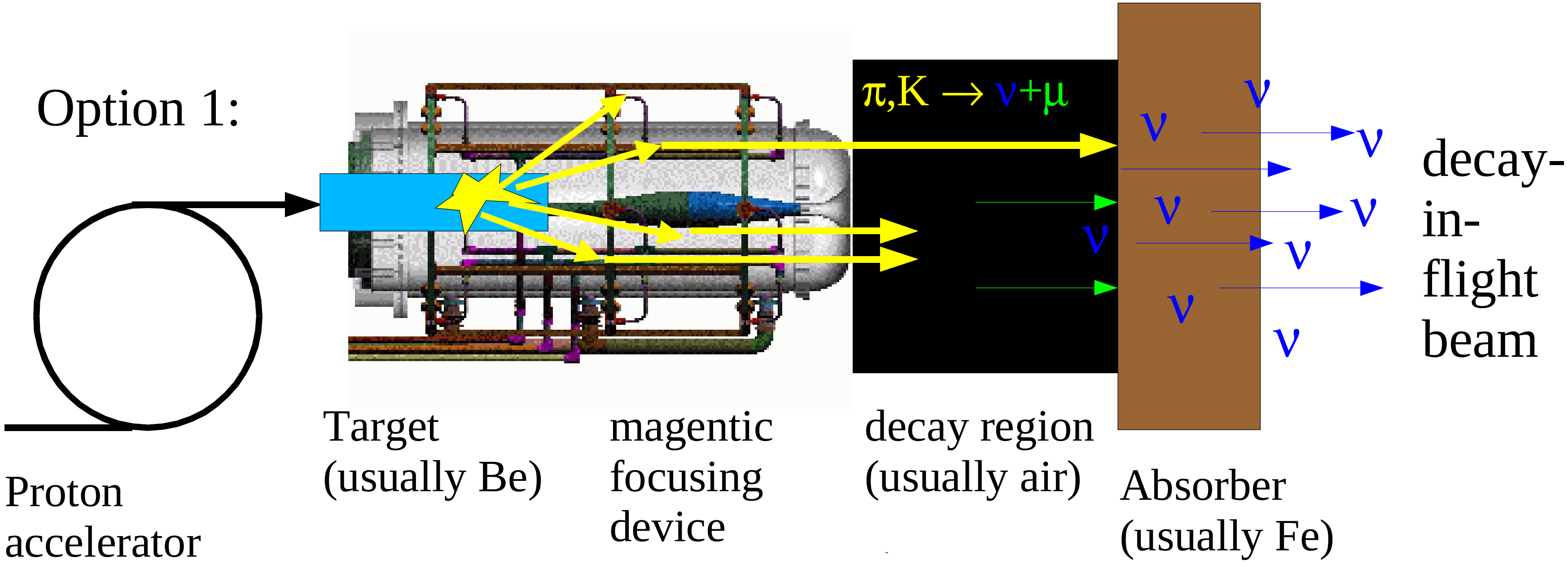
Rocky terrain: LSND

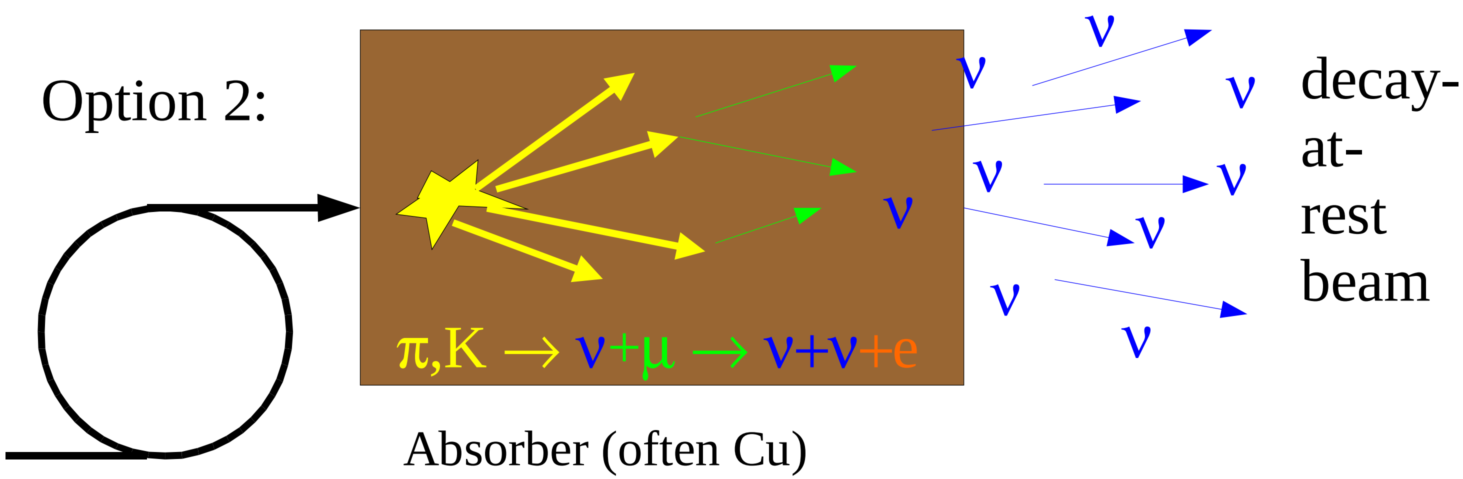
Terra incognita: The future

But first:

Why accelerators are the way to go...

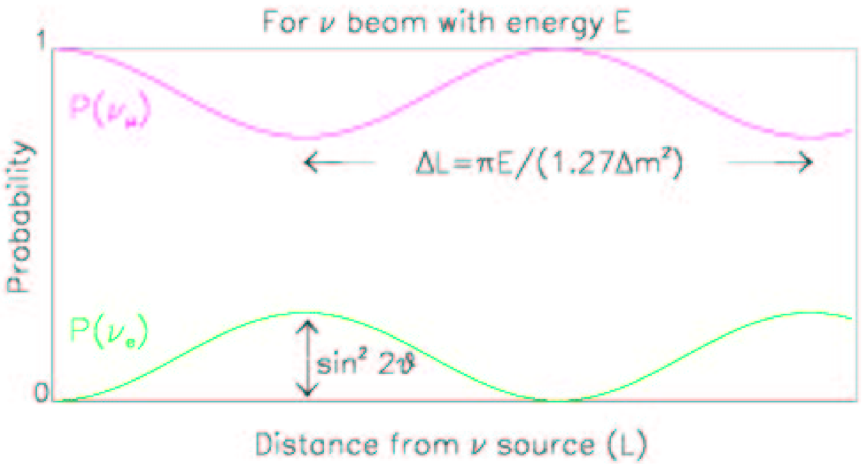
Making Neutrino Beams at Proton Accelerators





Accelerators give you more control.

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2(1.27 \Delta m^2 L/E)$$



ν_μ disappearance

ν_e appearance

Oscillation Probability depends on:

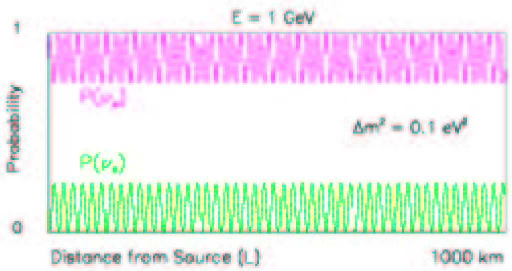
- Two fundamental parameters
  - Δm^2
  - $\sin^2 2\theta$
- Two experimental parameters
  - L: distance from source to detector
  - E: Neutrino energy

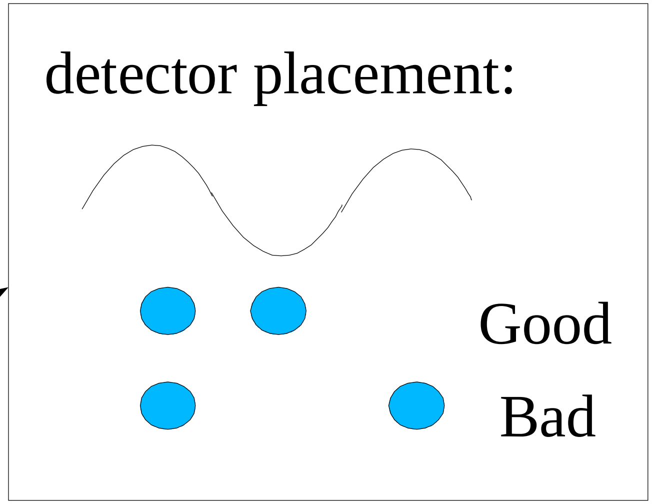
You can pick your L & E to select sensitivity to a specific range of Δm^2

L/E, Intensity and Sensitivity

$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

- Small $\Delta m^2 \to$ small P_{osc}
  Unless the experiment has large L/E to compensate!
- Large $\Delta m^2 \to$ oscillations happen rapidly
  For a single ν energy:

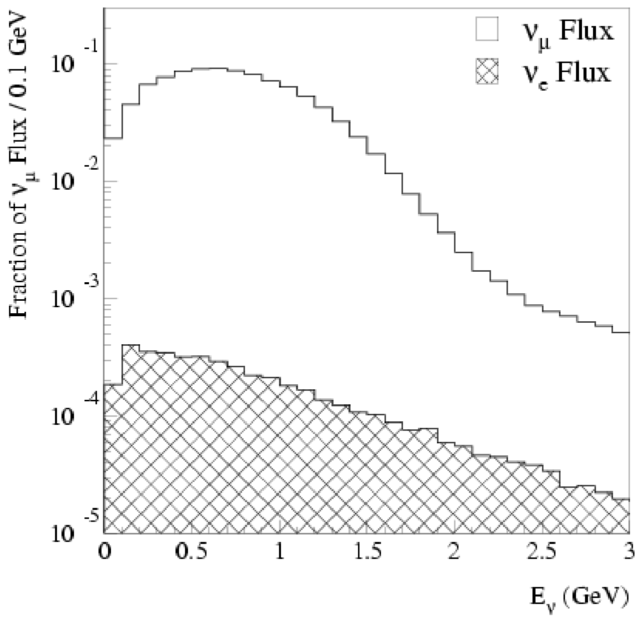




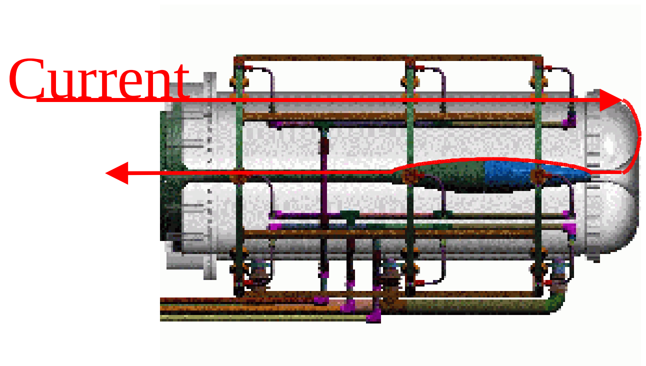
But beams have a wide E range,
detectors have finite resolution and large size:
. $\langle \sin^2(1.27\Delta m^2 L/E) \rangle = 1/2$
By choosing L/E too large,
You can lose sensitivity to Δm^2

- Small $\sin^2 2\theta \to$ small probability,
  So an experiment needs high statistics

L is a discrete choice
E is always a distribution (in nearly all neutrino experiments!)

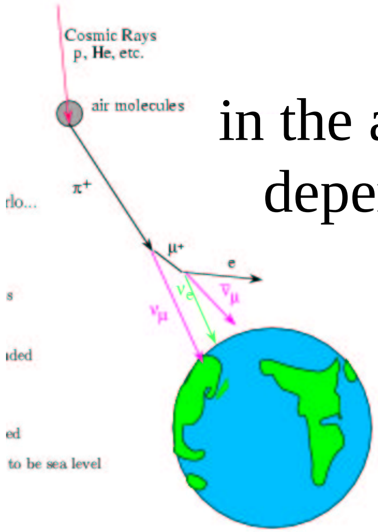


The peak position depends on:
energy of incoming protons
magnetic focusing of secondaries
using *horns*

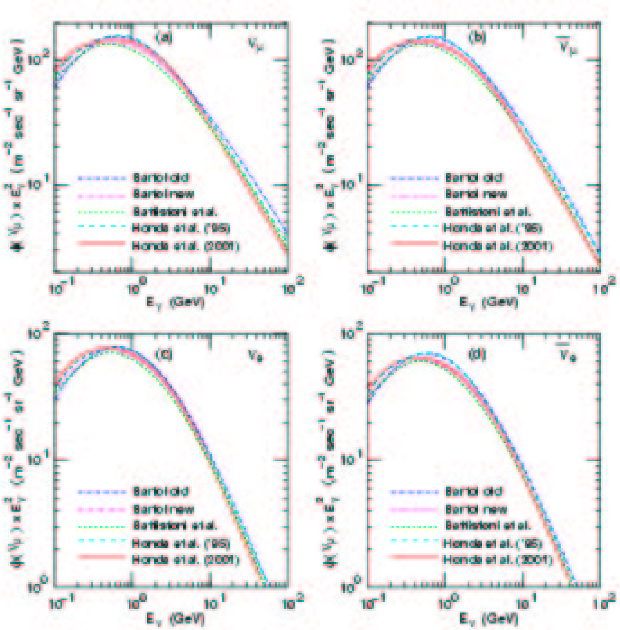


Decay-at-rest beams: up to 50 MeV
Decay in flight beams: up to 300 GeV

You also have more control over the neutrino flavor

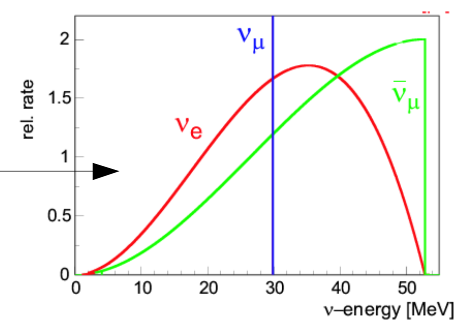


in the atmosphere ν_μ/ν_e depends on energy



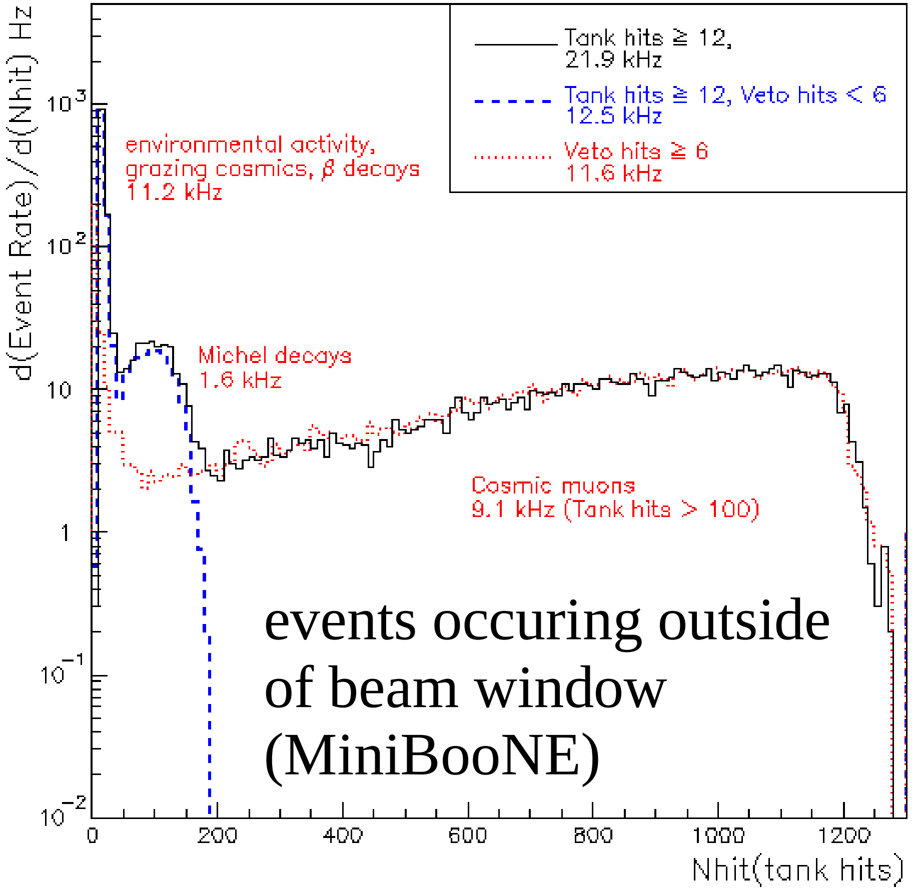
But accelerator beams can be made of nearly pure ν_μ
(Decay in flight)

Or with a well established flavor content
(Decay at rest)

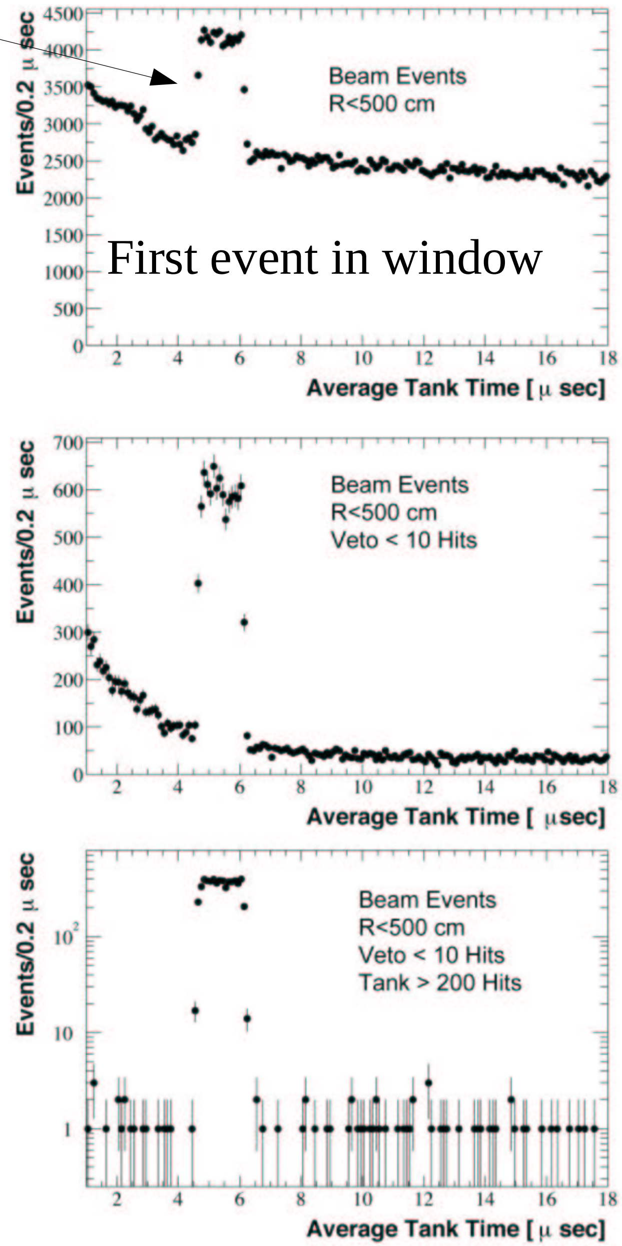


Beam timing makes the signal easy to identify over backgrounds...

The 1.6 μs spill at MiniBooNE

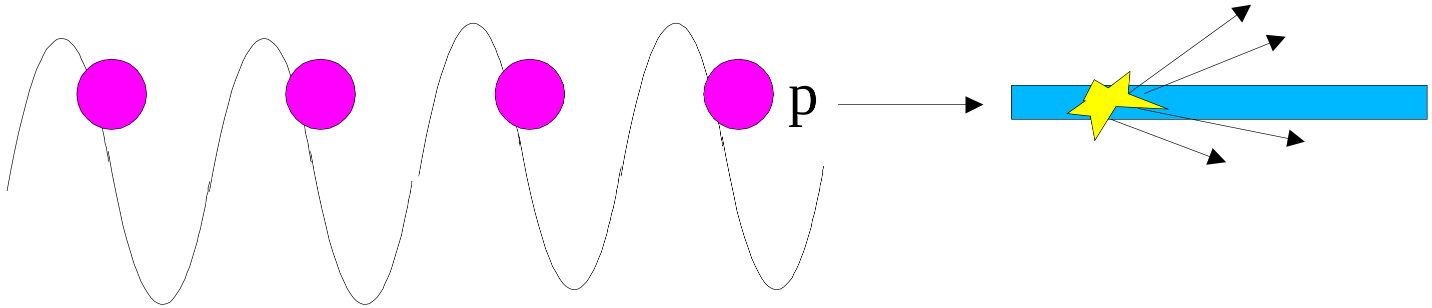


events occuring outside of beam window (MiniBooNE)



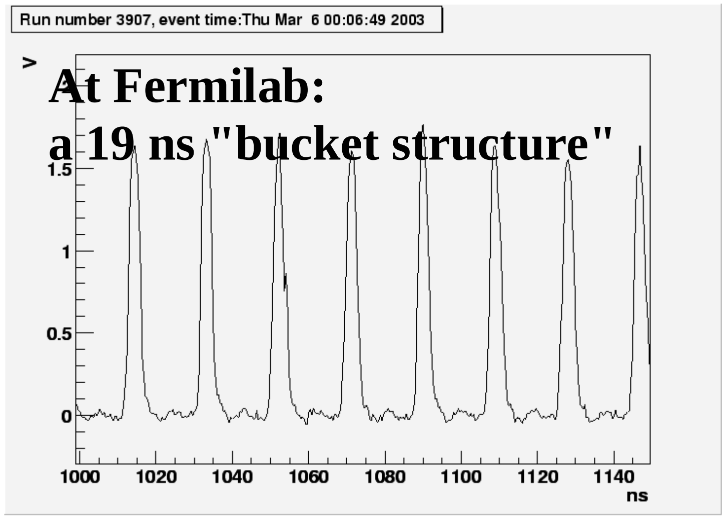
First event in window

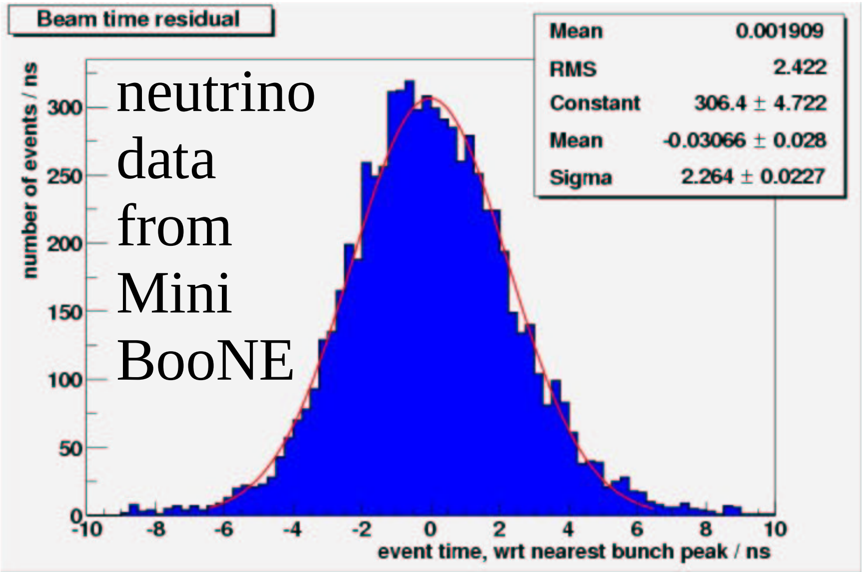
It is even possible to see the fine timing...



A clear timing structure from the RF

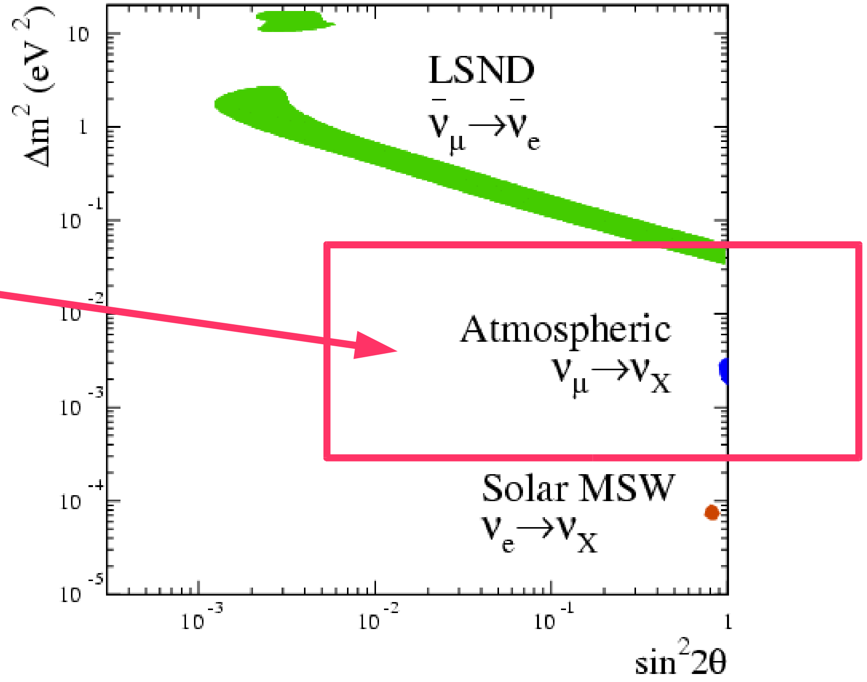
RF Wave





Timing cuts result in a significant reduction of background.

Exploration #1: Understanding the atmospheric oscillation signal



Super K has seen a deficit of ν_μ, but...

- Is it really $\nu_\mu \rightarrow \nu_\tau$?
- Is there no other component?
- What is the correct Δm^2?
- Is the mixing angle maximal?

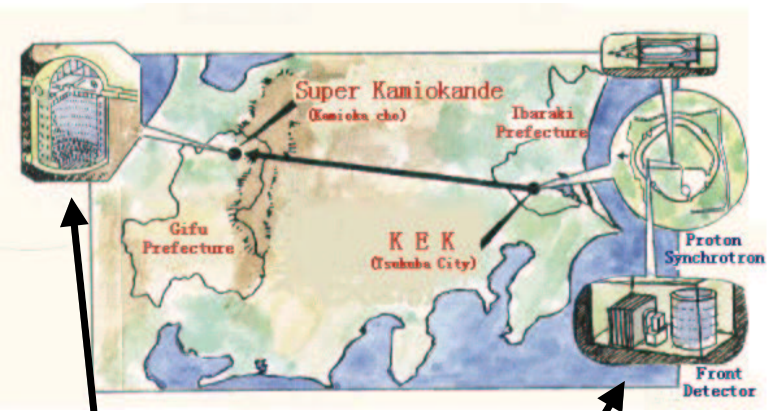
To study Δm^2~1E-3
you need L/E~1E3

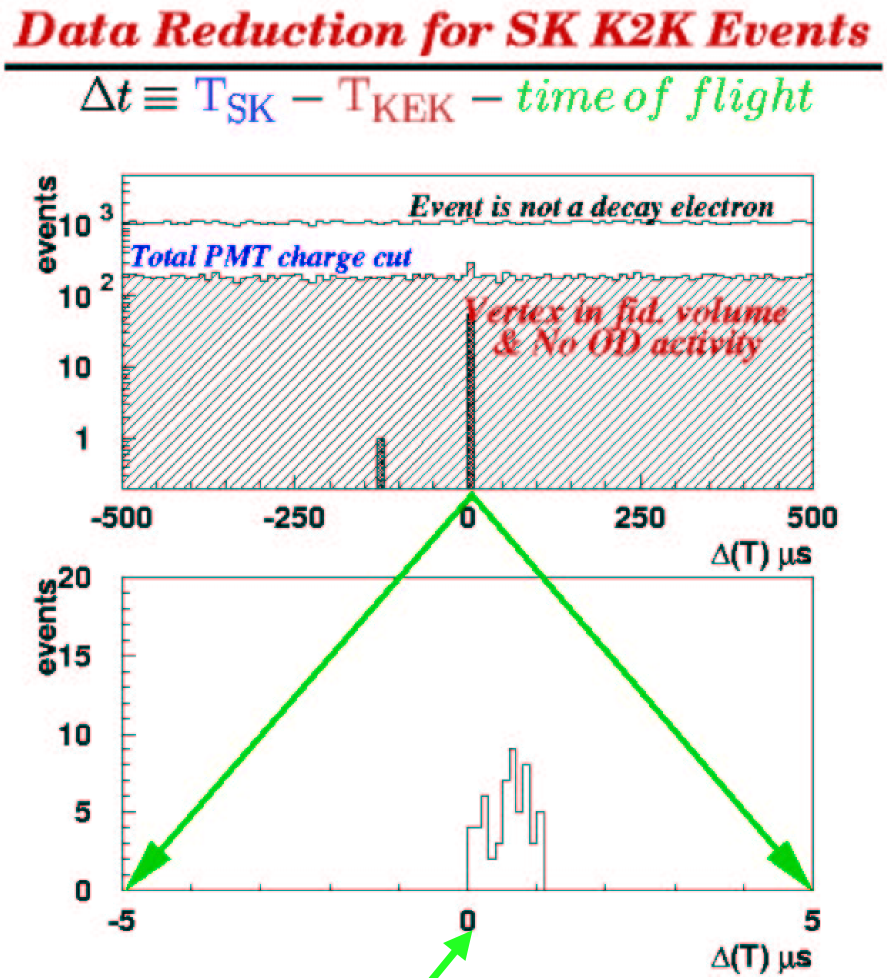
if E~1 GeV
then L~1000 km

K2K experiment:

accelerator based

ν_μ disappearance





~1GeV neutrino beam

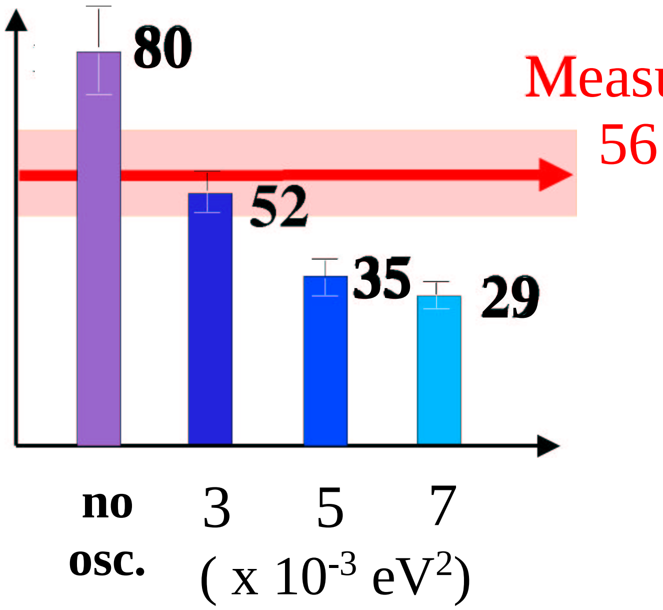
near detector at KEK

~250 km away

SuperK detector

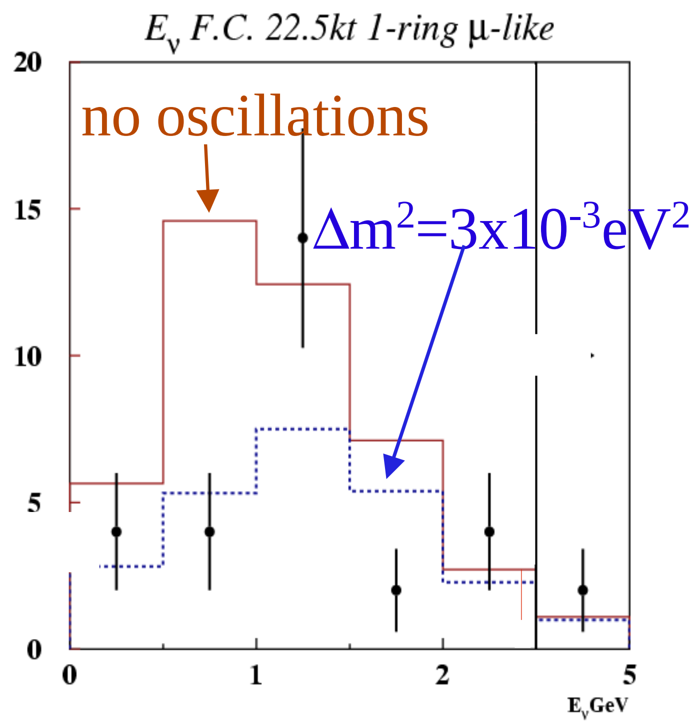
Accelerator produced events are well isolated by the timing!

Results on atmospheric anomaly with K2K



Expected ν_μ events:

~2σ signal consistent with Super-K results

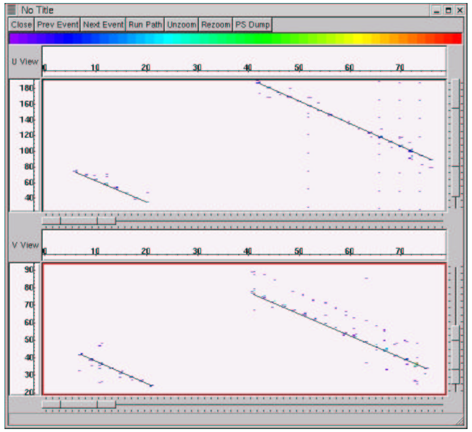


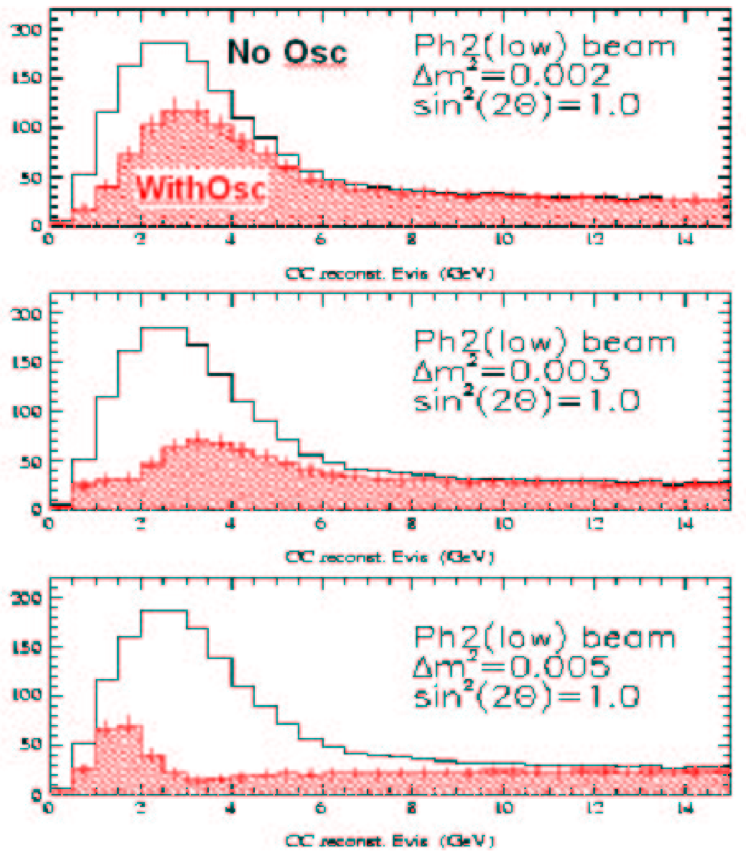
Energy spectrum

K2K was a crucial proof of principle & has added useful info,
but it will always be statistics limited. We need new experiments!

MINOS: ν_μ beam from FNAL to Soudan in Minnesota

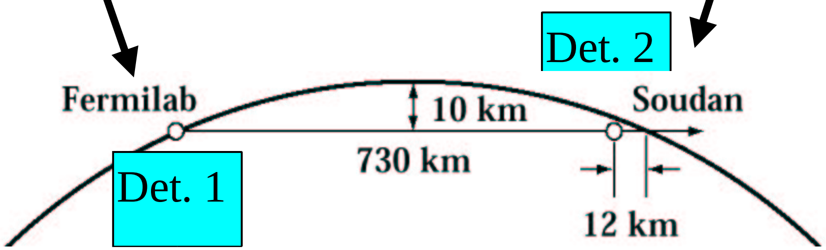
E ~ 2 GeV
L = 730 km



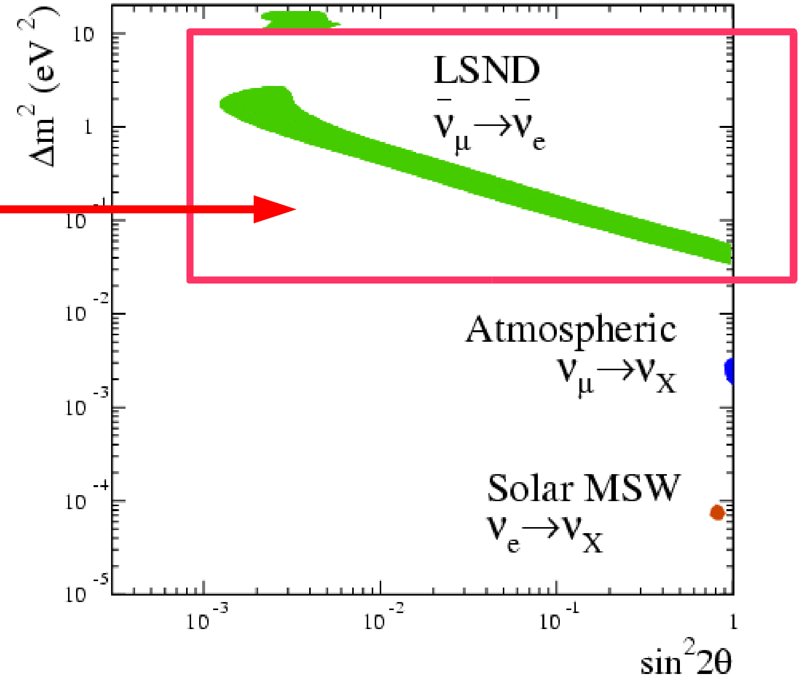


Far Detector:
segmented Iron calorimeter detecto

Near Detector



Exploration #2: Understanding the LSND oscillation signal



LSND has seen ν_e appearance in a ν_μ beam but...

- Is it really oscillations?
- If so how can we explain that?

Problem:

ν_1

Δm_{12}^2

ν_2

Δm_{23}^2

ν_3

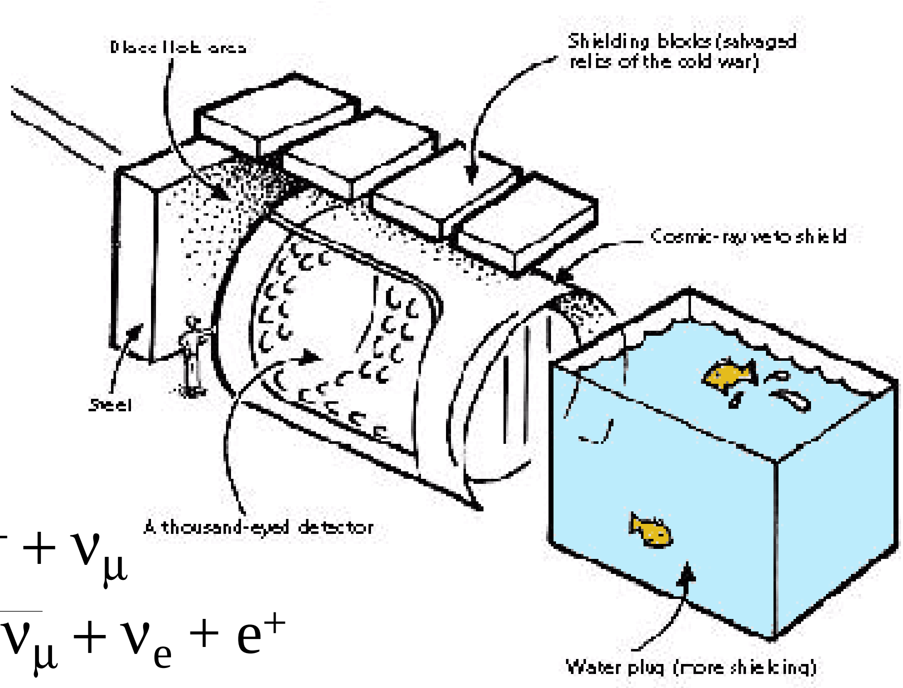
$$\Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2$$

The LSND Experiment at LANL
(1993-1998)

- accelerator based
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance

Neutrino Energy
E = 20-55 MeV

Baseline 30 m



Beam:
mostly --
decay at rest (ν_μ)

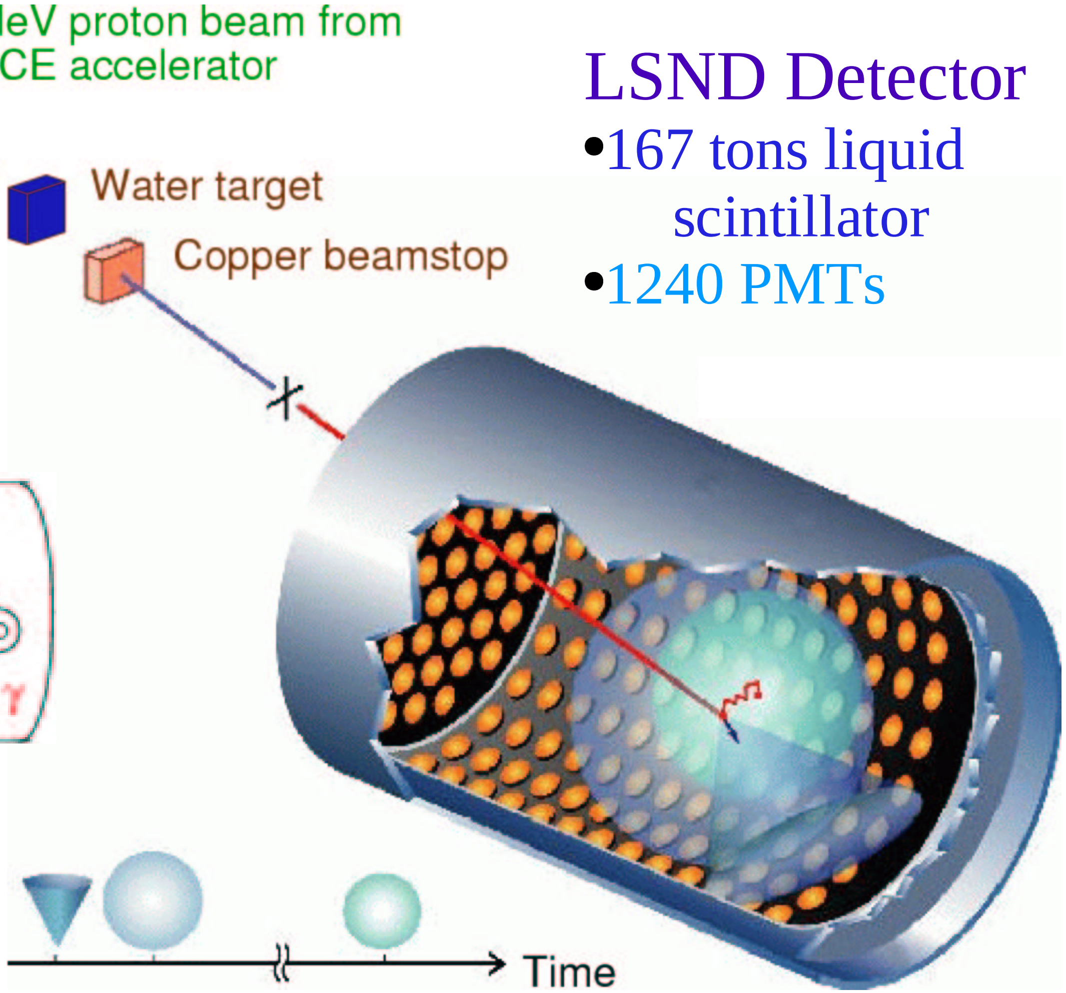
stopped $\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\hookrightarrow \bar{\nu}_\mu + \nu_e + e^+$

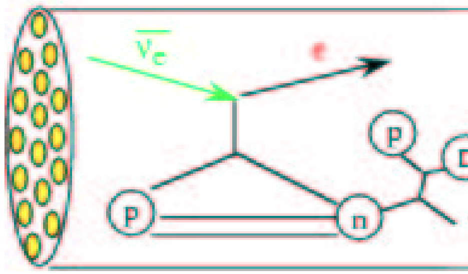
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$???

LSND Detector

- 167 tons liquid scintillator
- 1240 PMTs



$\bar{\nu}_e$ appearance

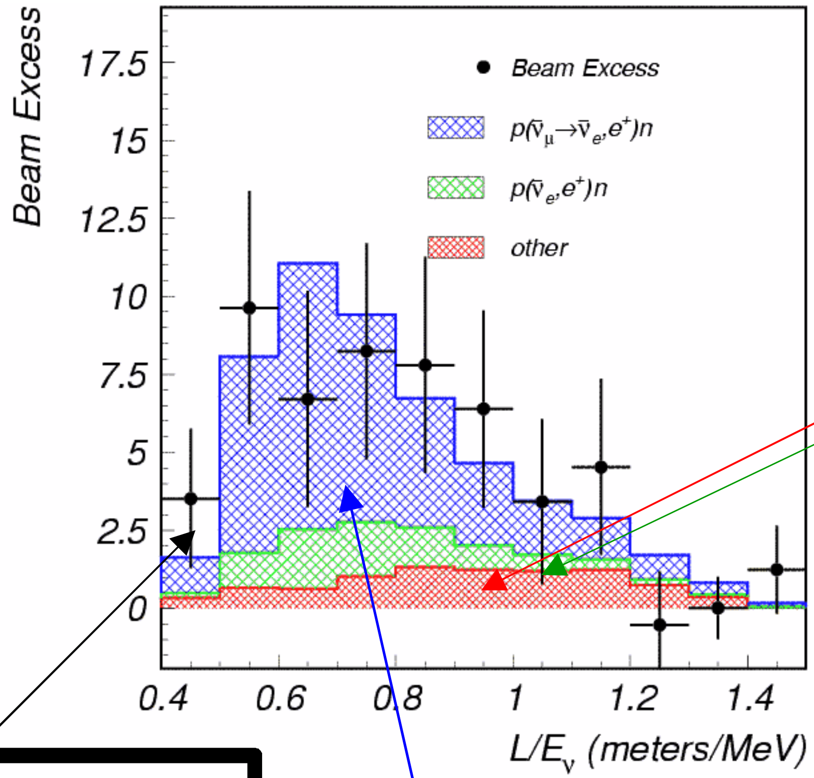


Tag $\bar{\nu}_e$s from CC interaction and subsequent neutron capture

The LSND Signal

Observe
87.9 ±22.4±6.0
ν_e appearance events

Oscillation Probability:
0.264
±0.067±0.045 %



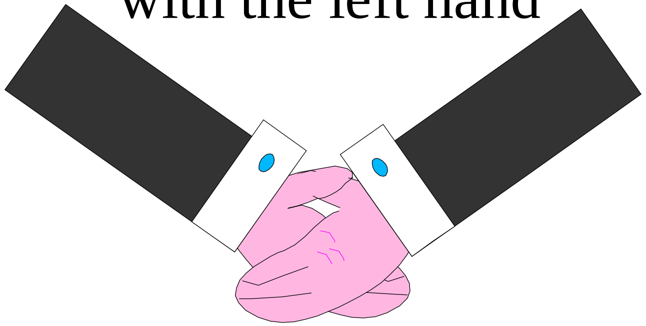
Size of the Beam-related backgrounds

Data points: Excess after Beam-off subtraction

Expectation for oscillations (Δm^2=0.24 eV^2)

"The W only shakes
with the left hand"

But so far we have only considered left handed neutrinos



These participate in the weak interaction.

In principle there could be right-handed neutrinos. They just would not interact

"**Sterile Neutrinos**"

Not in the Standard Model!

Strictly left-handed neutrinos ⟺ Massless Neutrinos

Because a Dirac neutrino mass term
in the SM Lagrangian looks like:

$$m(\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L)$$

But now we know that neutrinos have mass...

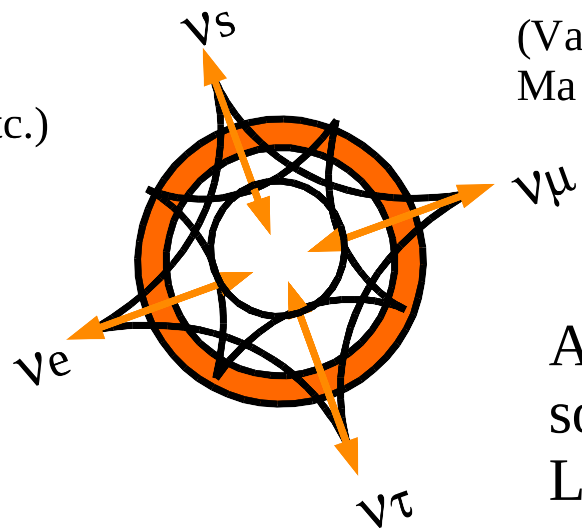
Massive neutrinos imply there are right-handed neutrinos.

"Sterile Neutrinos"
cannot interact via the weak interaction

But they could oscillate to standard model neutrinos

Super Symmetry
(Dvali +, hep-ph/9810257,
Arkani-Hamed +, hep-ph/0006312, etc.)

Grand Unified Theories
(Mohapatra, hep-ph/017264,
McKeller + , hep-ph/0106121, etc.)



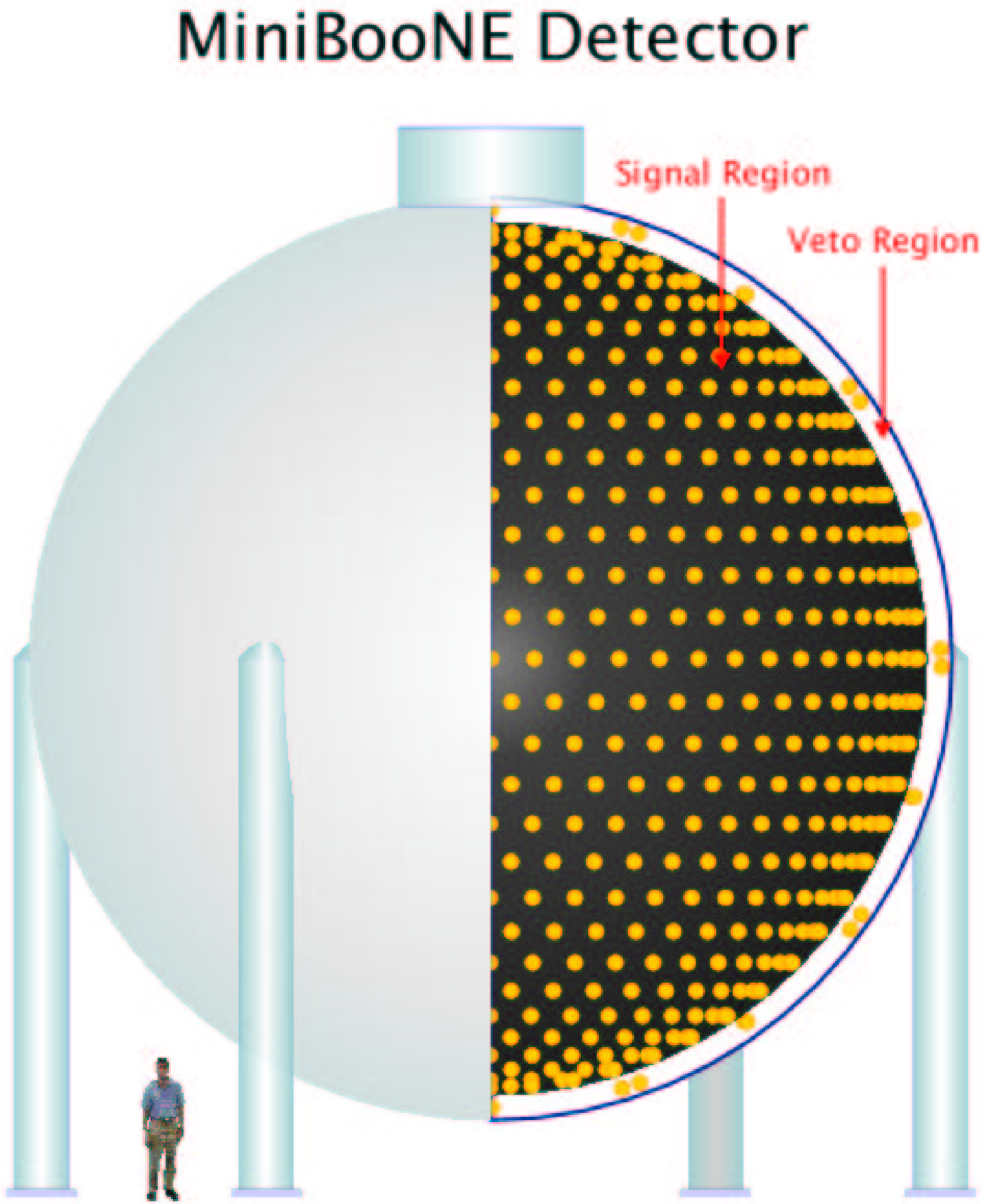
Extra Dimensions:
(Valle +, PRD63 073002,
Ma +, hep-ph/0006340, tec)

An extra neutrino
solves the
LSND problem

MiniBooNE at Fermilab:

Test LSND
in a new E range
thus a different L range
so that L/E is the same.

Expect results in 2005!



Exploration #3: Whither accelerator-based neutrino physics?

A Neutrino Factory

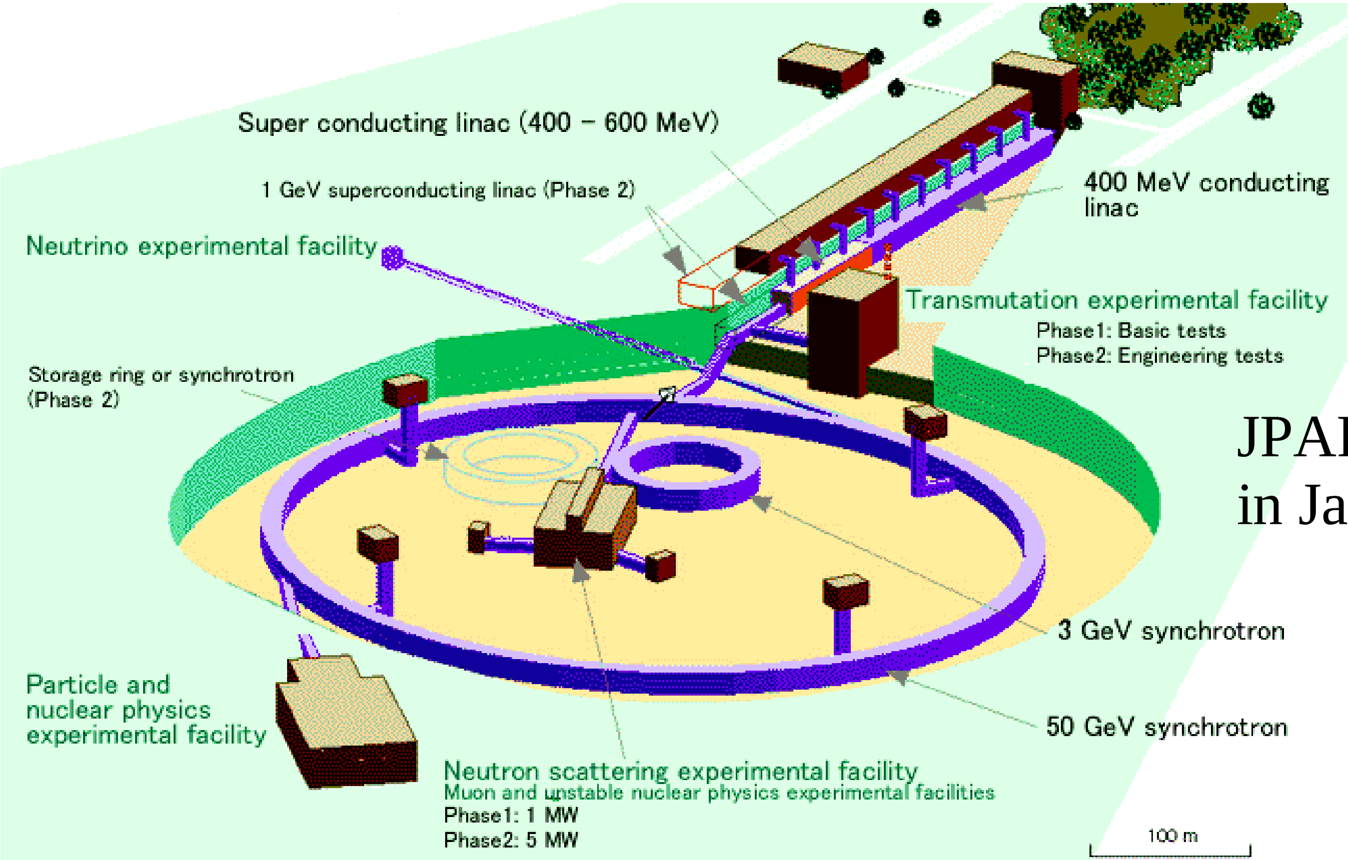
Proton Drivers:
JPARC,
A US Proton Driver?

An important upcoming question!

Near Term:
MINOS, CNGS, MiniBooNE

Neutrino measurements are statistics limited....need lots of protons!

Future high intensity proton sources output $>10^{22}$ Protons/year!



JPARC
in Japan

A neutrino experiment

can never be too big or have too many protons!

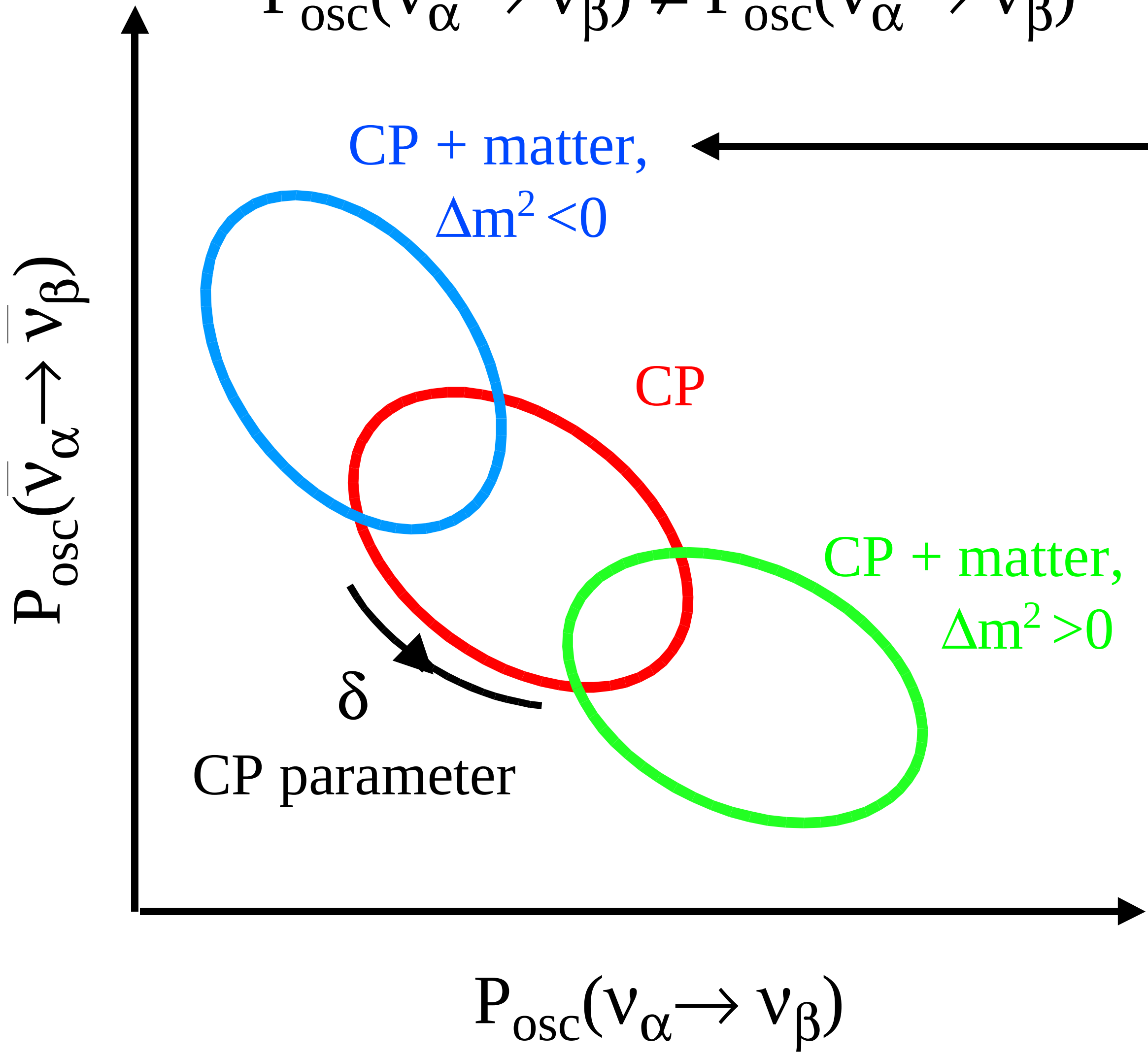
Important to the next step in oscillation measurements

CP violation

$$P_{osc}(\nu_\alpha \rightarrow \nu_\beta) \neq P_{osc}(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$$

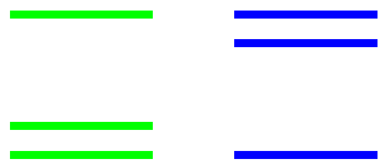
Leptogenesis $\rightarrow$ Baryogenesis

Baryon excess



matter effects modify this too!

$\Delta m^2 > 0$ $\Delta m^2 < 0$



To untangle, you need different baselines!

Not just for oscillations...
For example: Neutrino Magnetic Moments

Sensitive to beyond-the-Standard-Model theories!

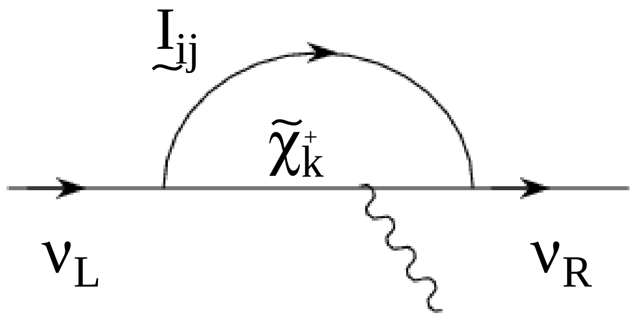
Minimally Extended Standard Model $\qquad \mu_\nu = \frac{3eG_F}{8\sqrt{2}\pi^2} m_\nu \sim 3 \times 10^{-19} \mu_B$

SUSY models$\rightarrow$left-right supersymmetric models

$\mu_{\nu_e} \cong 5.34 \times 10^{-15} - 10^{-16}\ \mu_B$

$\mu_{\nu_\mu} \cong 1.13 \times 10^{-12} - 10^{-13}\ \mu_B$

$\mu_{\nu_\tau} \cong 1.9 \times 10^{-12}\ \mu_B$



Large Extra Dimensions

$\mu_\nu \cong 1.0 \times 10^{-11}\ \mu_B$

Present limits are about
an order of magnitude away...

And non-neutrino physics also!

- An excellent neutron source
- Interesting low energy muon beams
- Medical applications

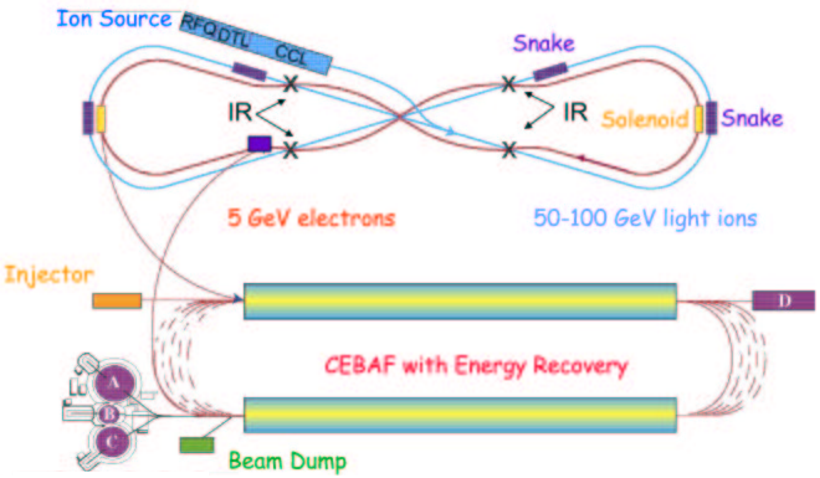
Proposals to build a Proton Driver in the US:

BNL

Fermilab

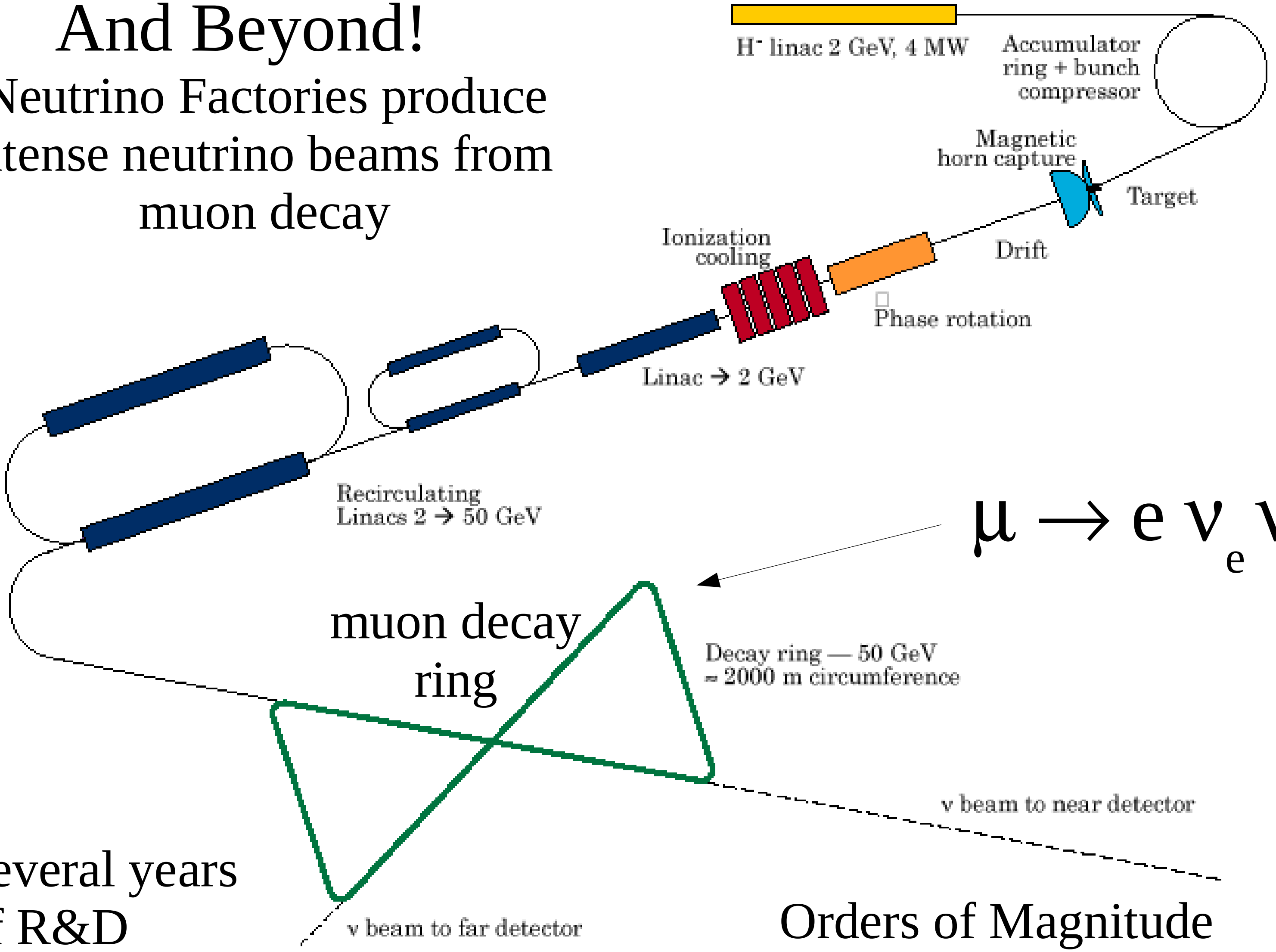
Jefferson Lab (?)

An important opportunity for the U.S. to pursue!



And Beyond!

Neutrino Factories produce intense neutrino beams from muon decay



$$\mu \rightarrow e\,\nu_e\,\nu_\mu$$

Several years of R&D away.

Orders of Magnitude more muon AND electron neutrinos

Conclusions:

Accelerators allow better experimental control,
hence higher precision

Already the program is varied and exciting:
coming soon: More from K2K
First results from MiniBooNE
The startup of Minos and CNGS

There is great potential for future proton drivers
and perhaps a neutrino factory

This is rich territory to explore!